

Chemical equilibrium study at SPS 158A GeV

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Abstract. A detailed study of chemical freeze-out in nucleus-nucleus collisions at beam energy 158A GeV is presented. By analyzing hadronic multiplicities within the statistical hadronization approach, the chemical equilibration of p-p, C-C, Si-Si and Pb-Pb systems is studied as a function of the number of participating nucleons in the system. Additionally, the Two Component statistical hadronization model is applied to the data and is found to be able to explain the observed strangeness hadronic phase space under-saturation.

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1. The statistical hadronization model

The main idea of the SHM is that hadrons are emitted from regions at statistical equilibrium. No hypothesis is made about how statistical equilibrium is achieved; this can be a direct consequence of the hadronization process [1]. In a single collision event, there might be several clusters with different collective momenta, different overall charges and volumes. However, Lorentz-invariant quantities like particle multiplicities are independent of clusters' momenta.

Depending on the system size, statistical analysis can be done in different statistical ensembles, which have been studied carefully by different groups and methods suitable for relativistic nucleus-nucleus collisions are well established [2]. In this work, small systems with net baryon number less than 10 are calculated in the BSQ -canonical ensemble taking into account exact conservation of B , S and Q charges. For the systems with the number of participants (N_P) between 10 and 100, exact conservation of strangeness only is taken into account while larger systems are treated grand-canonically (GC).

In spite of the appropriate ensemble, theoretical multiplicities are calculated within the main version of the statistical model by fitting temperature T , scaling volume V , and strangeness suppression factor γ_S [3]. Additionally, one needs to introduce a chemical potential for all charges that are treated in a GC manner. Usually the baryon chemical potential is taken as a free fit parameter, while the strangeness chemical potential is fixed by assuming net strangeness neutrality in the system and the chemical potential for electric charge by assuming that Q/B in the system equals Z/A of the colliding nuclei.

The overall multiplicity to be compared with the data, is calculated as the sum of primary multiplicity and the contribution from the decay of heavier hadrons: $\langle n_j \rangle = \langle n_j \rangle^{\text{primary}} + \sum_k \text{Br}(k \rightarrow j) \langle n_k \rangle$, where the branching ratios are taken from the latest issue of the Review of Particle Physics [4].

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Parameters	SHM(γ_S)	SHM(γ_S)	SHM(TC)	SHM(γ_S)	SHM(TC)
	p-p 158A GeV	C-C 158A GeV		Si-Si 158A GeV	
T (MeV)	177.3 \pm 5.2	165.7 \pm 4.1	170 \pm 10	163.0 \pm 4.7	162.0 \pm 7.6
μ_B (MeV)		248.1 \pm 12.5		245.5 \pm 11.0	234.4 \pm 22.5
γ_S	0.445 \pm 0.020	0.575 \pm 0.042	1.0 (fixed)	0.664 \pm 0.050	1.0 (fixed)
V	0.128 \pm 0.005	0.84 \pm 0.05	0.23 \pm 0.03	2.10 \pm 0.13	0.91 \pm 0.11
$\langle N_c \rangle$			6 \pm 0.4		11.4 \pm 1.8
χ^2/dof	13.0/7	3.4/4	5.8/5	7.6/4	1.0/4

Table 1. Summary of fitted parameters ($V=VT^3 \exp[-0.7 \text{ GeV}/T]$) at top SPS beam energy in the framework of the SHM(γ_S) model and SHM(TC).

2. Experimental data set and analysis results

The experimental data consists of measurements made by the NA49 collaboration in central p-p, C-C, Si-Si and Pb-Pb collisions at beam momenta 158A GeV [5, 6, 7, 8, 9, 10, 11]. The analysis has been carried out by looking for the minimum of the $\chi^2 = \sum_i \frac{(n_i^{\text{exp}} - n_i^{\text{theo}})^2}{\sigma_i^2}$. The fitted parameters within the main scheme SHM(γ_S) are shown in Table 1. A major result of these fits is that γ_S is monotonically increasing as a function of the number of participating nucleons, and significantly smaller than 1 in all cases (see Fig.1), thus strangeness seems to be under-saturated with respect to a completely chemically equilibrated hadron gas. This confirms previous findings [12, 13, 14, 15].

2.1. Superposition of NN collisions with an equilibrated fireball

In the Two Component model (SHM(TC)), first introduced in [12], the observed hadron production is taken as the superposition of two components: one originated from a large fireball at complete chemical equilibrium at freeze-out, with $\gamma_S = 1$, and another component from single nucleon-nucleon collisions. Since it is known that in NN collisions strangeness is strongly suppressed, the idea is to ascribe the observed under-saturation of strangeness in heavy ion collisions to the NN component.

With the simplifying assumption of disregarding subsequent inelastic collisions of particles produced in those primary NN collisions, the overall hadron multiplicity can be written then as $\langle n_j \rangle = \langle N_c \rangle \langle n_j \rangle_{NN} + \langle n_j \rangle_V$, where $\langle n_j \rangle_{NN}$ is the average multiplicity of the j^{th} hadron in a single NN collision, $\langle N_c \rangle$ is the mean number of single NN collisions and $\langle n_j \rangle_V$ is the average multiplicity of hadrons emitted from the equilibrated fireball. To estimate $\langle n_j \rangle_{NN}$ in np and nn collisions, the parameters (see Table 1) of the statistical model determined in pp are retained and the initial quantum numbers are changed accordingly. Theoretical multiplicities have been calculated in the canonical ensemble, which is described in detail in ref. [16].

This model was seen to be able to reproduce the experimental particle multiplicities measured in the Pb-Pb collisions at 158A GeV [12, 17]. For the Si-Si system, T , V , μ_B of the central fireball and $\langle N_c \rangle$ were fitted using the S-canonical ensemble in the central fireball. The fit quality is significantly improved compared to the main version of the statistical model, if the number of "single" NN collisions is about 11 with a 16% uncertainty.

The central fireball produced in the C-C system needs to be analyzed in the *BSQ*-canonical ensemble taking into account the actual proton-neutron configurations. The Two Component model can be used to describe the C-C system as well, if the total

baryon number in the central fireball is $B = N_p + N_n \approx 4$. Even though fit quality is slightly worse than with the main version of the statistical model, experimental multiplicities are well reproduced with the SHM(TC) also.

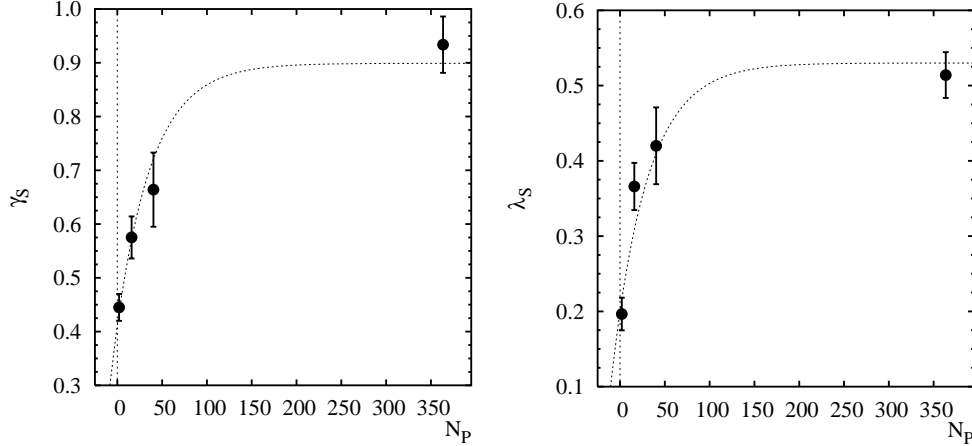


Figure 1. The strangeness non-equilibrium parameter γ_S and the corresponding λ_S factor as a function of the number of participating nucleons in the collision system (Pb-Pb from [12]). Both lines are of the functional form $f(N_p) = A - e^{-B N_p}$ and are plotted to guide the eye. Whenever the resulting $\chi^2/dof > 1$ in the fit, errors have been re-scaled by factor $\sqrt{\chi^2/dof}$, for details see [4, 12]. From left to right: p-p, C-C, Si-Si and Pb-Pb.

3. System size dependence and conclusions

Our fit results show non-trivial system size dependence of chemical equilibration and characteristic thermal parameters of the source in ultra-relativistic heavy ion collisions. The chemical freeze-out of all the different systems, C-C, Si-Si and Pb-Pb with beam momenta 158A GeV seem to happen at similar chemical state, all of them at $\mu_B \approx 250$ MeV. Such weak system size dependence of the baryon chemical potential has been already reported earlier [15].

Systems with few participating nucleons seem to decouple at slightly higher temperature than heavy systems, but in general the chemical freeze-out temperature as well as the baryon chemical potential are determined mostly by the beam energy, not by the number of participants, and thus C-C, Si-Si and Pb-Pb with the same beam momenta, seem not to follow the chemical freeze-out curve (see Fig. 2), but show more complex system size dependence, an interplay of the initial beam energy and the number of participants in the system.

The chemical equilibration of strangeness, on the other hand, seems to be strongly dependent on the number of participants. Going from small to large systems, the γ_S parameter increases monotonically from 0.45 in the p-p to 0.9 in the Pb-Pb with the same beam momenta, and thus strangeness seems to be out of equilibrium in all collision systems studied at SPS. The Wroblewski variable $\lambda_S = 2\langle s\bar{s} \rangle / (\langle u\bar{u} \rangle + \langle d\bar{d} \rangle)$, the estimated ratio of newly produced strange quarks to u and d quarks at primary hadron level, features very similar suppression in strangeness production, see Fig. 1.

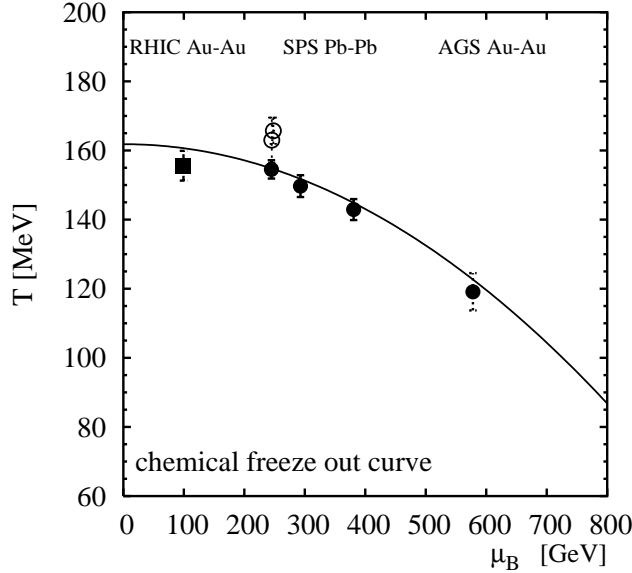


Figure 2. Chemical freeze-out points in the $[\mu_B - T]$ plane in various heavy ion collisions. Full round dots [12] refer to the Au-Au at 11.6 and Pb-Pb collisions at 40, 80, 158A GeV, whilst the square dot has been obtained by applying the statistical model to the preliminary π^+ , π^- , K^+ , K^- and N_P multiplicities [18] in the Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The hollow round dots refer to the C-C and Si-Si collisions at 158A GeV. Whenever the resulting $\chi^2/dof > 1$ in the fit, errors have been re-scaled by factor $\sqrt{\chi^2/dof}$, for details see [4, 12].

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